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A review of solar thermal technologies[☆]

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ABSTRACT

The use of solar energy in recent years has reached a remarkable edge. The continuous research for an alternative power source due to the perceived scarcity of fuel fossils is its driving force. It has become even more popular as the cost of fossil fuel continues to rise. The earth receives in just 1 h, more energy from the sun than what we consume in the whole world for 1 year. Its application was proven to be most economical, as most systems in individual uses requires but a few kilowatt of power. This paper reviews the present day solar thermal technologies. Performance analyses of existing designs (study), mathematical simulation (design) and fabrication of innovative designs with suggested improvements (development) have been discussed in this paper.

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1. Introduction

Of all the renewable sources of energy available, solar thermal energy is the most abundant one and is available in both direct as well as indirect forms. The Sun emits energy at a rate of 3.8×10^{23} kW, of which, approximately 1.8×10^{14} kW is intercepted by the earth, which is located about 150 million km from the sun. About 60% of this amount or 1.08×10^{14} reaches the surface of the earth. The rest is reflected back into space and absorbed by the atmosphere. About 0.1% of this energy, when converted at an efficiency of 10% would generate four times the world's total generating capacity of about 3000 GW. It is also worth noting that the total annual solar radiation falling on the earth is more than 7500 times the world's total annual primary energy consumption of 450 EJ. The annual solar radiation reaching the earth's surface, approximately 3,400,000 EJ, is an order of magnitude greater than all the estimated (discovered and undiscovered) non-renewable energy resources, including fossil fuels and nuclear. However, 80% of the present worldwide energy used is based on fossil fuels. Risks associated with their use are that they are all potentially vulnerable to adverse weather conditions or human acts. World demand for fossil fuels (starting with oil) is expected to exceed annual production, probably within the next two decades. International economic and political crisis and conflicts can also be initiated by shortages of oil or gas. Moreover, burning fossil fuels release harmful emissions such as carbon dioxide, nitrogen oxides, aerosols, etc. which affect the local, regional and global environment.

2. Solar water heaters

2.1. Study

Chang et al. studied the solar irradiation patterns for the performance testing of thermosyphon solar water heaters and concluded that a distribution factor R_i and its criterion have to be introduced into the CNS test standard to provide reliable test results for solar hot water heaters [1]. Mathioulakis and Belessiotis investigated the performance of a new solar hot water system with an integrated heat-pipe and compared the proposed theoretical model of the collector with the experimental results [2]. Chang et al. evaluated the thermal performance and heat removal efficiency of 12 different types of thermosyphon solar water heating systems and suggested a criterion of modified efficiency of $\eta_o \geq 0.41$ [3]. Abreu and Colle experimentally analyzed the thermal behaviour of two-phase closed thermosyphons with an unusual geometry characterized by a semicircular condenser and a straight evaporator [4]. Morrison et al. investigated the characteristics of horizontal mantle heat exchangers for application in thermosyphon solar water heaters and found out that configurations of mantle heat exchangers used in current solar water heater applications degrade thermal stratification in the inner tank [5]. Kerdchang et al. studied the performance of a Beta Stirling solar thermal engine system, determined the power output and actual heat transfer on the performance of the engine and showed that the regenerator volume and phase angle must be chosen carefully to fulfill the requirement that the total fluid mass in the system is constant and obtain maximum power output throughout the day [6]. Thur et al. analyzed the realistic behaviour and efficiency of heating systems based on long term monitoring projects and hence proved that the potential of fuel reduction can be a maximum of double the solar gain due to a strong increase of the system efficiency [7]. Esen and Esen performed experiments to study the effect of refrigerants on the thermal performance of a two-phase thermosyphon solar collector and investigated the performance of the system under clear-sky conditions with and without water load [8]. Madhlopa et al. studied the effect of tank-interconnection geometry on temperature stratification in an integrated collector-storage solar water heater with two horizontal cylindrical tanks [9]. Tanaka et al. examined the performance of three types of district heating/cooling and hot water supply systems with natural and unused energy utilization and found that if the amount of heating/cooling demand were well balanced, an improvement of energy performance could be achieved and the utilization factor of the seasonal tank would become higher [10]. Huang et al. studied a heat-pipe enhanced solar-assisted heat pump water heater, which uses dual heat sources that combines the performance of conventional heat pump and solar heat-pipe collector and built a prototype of the same [11]. Morrison et al. described the characteristics of horizontal mantle heat exchangers for application in thermosyphon solar water heaters [12]. Cristofari et al. studied the performance of a solar flat-plate thermal collector wholly manufactured in a copolymer material and analyzed the influence of different parameters of the system such as insulation thickness, flow rate and fluid layer thickness [13]. Crawford and Treloar analyzed the net energy requirement of solar hot water systems, including their embodied energy and found that the energy payback period of the electric- and gas-boosted solar hot water systems were 0.5 and 2 years for the respective same fuel based conventional hot water systems [14]. Hahne and Chen numerically studied the flow and heat transfer characteristics in a cylindrical hot water store during the charging process under adiabatic thermal boundary conditions and obtained a correlation of the numerical results for the design of effective hot water stores [15]. Chow et al. presented the performance evaluation of a new water-type PV/T collector system and showed that a payback period of 12 years for the PV/T collector system is comparable to the side-by-side system, and is much shorter than the plain PV application [16]. Furbo et al. presented the investigation of small Solar domestic hot water systems (SDHW) based on smart solar tanks and recommended to start development of smart solar tank units with an oil-fired boiler or a natural gas burner as auxiliary energy supply systems [17]. Hawlader and Jahangeer investigated the performance of a solar assisted heat pump dryer and water heater and suggested that the total drying time of the product decreases with the increase in drying potential [18]. Aye et al. compared three different water heating systems regarding their energy performance at various locations of installation using computational simulation and concluded that the appropriate

selection of the location of installation significantly contributes not only to the saving in hot water generation cost but also in reduction of greenhouse gases to the atmosphere [19]. Joshi et al. made a review of standards, based on steady state models and used for outdoor testing of thermosyphon-type solar domestic hot water system (TSDHWS) and evaluated three standards, concerning solar-only systems [20]. Al-Madani designed and evaluated the performance of a cylindrical solar water heater which suggested a good capability of the system to convert the solar energy to heat to be used for heating water [21]. Ho and Chen presented a theoretical prediction of the performance of a double-pass sheet-and-tube solar water heater with external recycle, compared it with that of a conventional type collector and showed that the recycle effect can effectively enhance the collector efficiency compared with that in a single-pass device with the same flow rate [22]. Lee and Sharma studied the year round thermal performance evaluation of active and passive solar water heating systems for rural/urban area and proved the feasibility of ethylene glycol as HTF for the active and passive solar water heating systems [23]. Morrison et al. discussed the factors influencing the operation of water-in-glass collector tubes and presented the numerical study of water circulation through long single-ended thermosyphon tubes [24].

2.2. Design

Belessiotis and Mathioulakis developed an efficient and simple simulation approach for thermosyphon solar water heaters and used the proposed methodology for energy optimization of the system in the design phase and for evaluation of test results of an existing system in order to improve it further [25]. Loomans and Visser described the implementation of the generic algorithm in a design support tool for solar hot water systems which allows optimization of separate variables such as the collector type, the number of collectors, the heat storage mass and the collector heat exchanger area [26]. Mills described the problems with the current modeling techniques and suggested that GIS can be used to generate much more detailed assessments of SHW system performance [27]. Shah et al. developed a CFD simulation model of vertical mantle heat exchanger for detailed evaluation of the heat flux distribution over the mantle surface which indicated that the distribution of the flow around the mantle gap is governed by buoyancy driven recirculation in the mantle [28]. Chaurasia and Twidell suggested that transparent insulation material may be successfully introduced in integrated collector-storage (ISC) solar water heaters to increase the efficiency and to provide hot water at higher temperature as compared to conventional ISC solar water heater with glass glazing [29]. Pillai and Banerjee proposed a methodology which links the micro-level factors and macro-level market effects affecting the diffusion or adoption of solar water heating systems for potential estimation of solar water heating in a target area [30]. Sanino and Reischel proposed different model structure types for a solar domestic water heating system and included physical knowledge in the form of non-linear regressors as a result of simple phenomenological modeling exercise [31]. Kalogirou et al. used artificial neural networks (ANN) to predict the useful energy extracted from the solar domestic water heating systems and stored water temperature rise with minimum of input data [32]. Mills and Morrison described a design approach taking the existing commercial flat plate absorber and tank components to use in a new way to maximize solar contribution and minimize material usage in the construction of the system [33]. Chyng et al. carried out a modeling and system simulation of an integral-type solar assisted heat pump water heater which assumes a quasi-steady process for all components in the integral-type solar assisted heat pump water heater (ISAHP) except the storage tank and showed that the expansion device does not need to be controlled online [34]. Razavi et al. determined the heat transfer rate for polypropylene tubes in solar water heaters for the Reynolds number range 800–5600 and used the data to predict heat transfer rates in a polypropylene solar heater [35]. Burch et al. detailed the modeling assumptions and simulation results for an unglazed collector system supplying domestic hot water, space heating, and space cooling loads [36]. Yohanis et al. proposed an approach for the analysis of the performance of solar water heating systems which determines the number of days in each month when solar heated water above a set temperature is available from the system [37]. Kalogirou and Panteliou used artificial neural networks (ANN) for the long-term performance prediction of thermosiphonic type solar domestic water heating (SDWH) systems and indicated that the proposed method can successfully be used for the prediction of the solar energy output of the system for a draw-off equal to the volume of the storage tank or for the solar energy output of the system [38]. Raab et al. validated the TRNSYS XST-model for the calculation of the thermal behaviour of ground buried hot water heat stores and found that the deviations between measured and calculated heat quantities do not exceed 5% [39].

2.3. Development

Nagaraju et al. designed and installed an industrial model solar water heating system to heat and supply 1,10,000 l of hot water at 85 °C per day, delivering the designed thermal output, and the net savings in furnace oil consumption being 78% on an annual basis [40].

3. Solar cookers

3.1. Study

Schwarzer and Vieira da Silva presented the experimental procedures to be used to calculate the parameters which determine the thermal performance of solar cookers and also suggested a simplified procedure based on energy balance equations for the design of solar cookers [41]. Ekechukwu and Ugwuoke presented the design philosophy, construction and measured performances of a plane-reflector augmented box-type solar-energy cooker which recorded a significant improvement in performance with the plane reflector in place [42]. Pohekara et al. discussed cooking energy dissemination in India with an objective of understanding the underlying socioeconomic factors governing the utilization of various fuels/energy carriers in cooking and also the policy interventions required for better dissemination of renewable energy based devices [43]. Algifri and Towaie outlined a method to find out the variation of a reflector performance factor and orientation factor with the elevation angle of the sun, solar surface azimuth angle and the reflector tilt angle for a square box cooker with single reflector [44]. Richard Petela presented the theoretical exergy analysis of a solar cooker, the distribution of the exergy losses in the cooker and the exergy analysis of the radiating surface absorbing radiation fluxes of different temperatures [45]. Negi and Purohit performed thermal performance tests on a box type solar cooker employing a non-tracking solar concentrator and showed that it can provide improved heat collection and hence more efficient cooking [46]. Harmim et al. investigated a finned cooking vessel in order to increase the efficiency of solar cookers and to reduce cooking time [47]. Pohekara and Ramachandran computed the utility of parabolic solar cooker (PSC) in India with respect to eight prevalent cooking devices by knowing users' preferences and expert opinion on thirty different criteria using the additive multi-attribute utility theory (MAUT) model for evaluation [48]. Talmatsky and Kribus compared the annual performance of a domestic hot water (DHW) system with phase change material

(PCM) in the storage tank, to that of a similar system without PCM, under the same conditions and concluded that the use of PCM in the storage tank does not yield a significant benefit in energy provided to the end-user mainly due to increased heat losses during night time caused by the reheating of the water by the PCM [49]. Gaur et al. made a performance study of the box type solar cooker with special emphasis on the shape of lid of the utensils used in a solar cooker and concluded that the performance can be improved if a utensil with a concave shape lid is used instead of a plain lid generally provided with the solar cooker [50]. Reddy and Rao compared the performance of the cooking vessel with depressed lid on lugs with that of the conventional vessel on lugs and found that the average improvement of performance of the vessel with depressed lid is 8.4% better than the conventional cylindrical vessel [51]. Reddy and Rao deals with a detailed theoretical and experimental study of the performance boost obtained by a cooking vessel with a central cylindrical cavity on lugs when compared to a conventional cylindrical vessel on lugs [52]. Biermann et al. studied the acceptance of solar cookers among various other cooking options in the household or institution [53]. Roca et al. presented the development and application of a feedback linearization control strategy for a solar collector field supplying process heat to a multi-effect seawater distillation plant [54]. Suharta et al. described the influences which govern solar box cookers: HS 7534, HS 7033 and the newest design HS 5521 [55]. Amer introduced and extensively investigated the performance of a novel design of solar cooker in which the absorber was exposed to solar radiation from the top and the bottom sides and a set of plane diffuse reflectors was used to direct the radiation onto the lower side of the absorber plate [56]. Buddhi et al. studied a cylindrical latent heat storage unit for the cooking pot of a solar cooker with three reflectors to store the solar energy during sunshine hours and to cook the food during the evening time in the winter season [57]. Sharma et al. investigated the thermal performance of a prototype solar cooker based on an evacuated tube solar collector with phase change material (PCM) storage unit [58]. Kumar et al. presented the performance results of experimental study conducted on solar pressure cooker and developed a simulation model for predicting the cooker performance under a variety of operating and climatic conditions [59].

3.2. Design

Mirdha and Dhariwal analyzed the various possible designs of tilted surface cookers with various positions of booster mirrors in the north–south direction as well as in the east–west and achieved a final optimized design of the solar cooker [60]. Mohamad et al. designed a simple wooden, hot box, with one reflector solar cooker and fabricated several demonstration units which showed acceptable performance on field testing [61]. Kumar discussed a thermal test procedure to determine the design parameters, which in turn, can be used to predict the heating characteristic curves (or thermal performance) of a box-type solar cooker [62]. Chaudhuri presented an estimate of electrical power requirement of a heater for an Indian Solar Box Cooker (SBC) considering its no-load figure of merit and energy balance at stagnation and also found that a 160 W heater is sufficient for cooking [63]. Ozturk applied the international standards for testing and reporting the solar cooker performance to the experimental determination of the energy and exergy efficiencies of the solar parabolic cooker and calculated the time-variations of these efficiencies based on the applied formulae and measurement data [64]. Franco et al. introduced some changes to the solar cooker consisting of two separate units: a concentrator on one side and an insulated box containing the pot on the other to improve its working capacity by using three different kinds of absorbers, which have been optimized to fulfill different functions in a concentrator of an area of 2 m^2 [65]. Kumar presented simple thermal analysis to evaluate the natural convective heat transfer coefficient for an absorber plate-inner glass trapezoidal enclosure of a double-glazed box-type solar cooker [66]. Chen et al. investigated the feasibility of selected PCMs as the storage medium in a box-type solar cooker to cook and/or to keep food warm in the late evening hours and also presented a two-dimensional theoretical model based on enthalpy formulation to predict the thermal performance of the storage system [67]. Mazloumi et al. simulated a solar single effect lithium bromide-water absorption cooling system in Ahwaz, which is one of the sweltering cities in Iran, where an enormous amount of energy is being consumed to cool residential places [68]. Saitoh and El-Ghetany presented a system which is used to produce relatively larger amounts of sterilized water than by merely putting a fixed amount of contaminated water in a small bottle inside a hot box solar cooker (HBSC) [69]. Esen demonstrated the feasibility of using refrigerants in a solar cooking system which consists of a vacuum-tube solar collector with integrated long heat-pipes leading directly to the oven plate, to cook and/or to keep food warm in the late evening [70]. Kumar developed a correlation for top heat loss coefficient U_{tw} for the water loaded cooker, based on indoor and outdoor experimental data as a function of pot water temperature, ambient temperature and wind speed [71].

3.3. Development

Mawire and McPherson developed, simulated and implemented experimentally a feed forward internal model control (IMC) structure for controlling the outlet charging temperature of a thermal energy storage (TES) and cooking system. They also found that the feedforward IMC structure performed better than the combined feedforward and PID feedback structure experimentally in terms of the stability in tracking the set temperature [72]. Sharaf revealed the concept of the conical focus and explained and tested the design of an economical, highly efficient, conical solar cooker [73]. Kumar et al. designed and fabricated a truncated pyramid-type solar cooker cum dryer which meets the standards prescribed by the Bureau of Indian Standards for solar box-type cookers and also recommended minor modifications to achieve higher temperatures and reduced cooking times [74]. Ali developed a solar box cooker to be used in Sudan and verified its acceptability [75]. Nandwani designed, constructed, studied and promoted solar oven, hybrid solar/electric oven, solar oven cum drier, solar cooker cum water heater and solar still which can be used at any time and for different uses but with the reduced consumption of conventional fuel [76]. Sharma et al. designed and fabricated a cylindrical latent heat storage unit for the cooking pot of a solar cooker to store solar energy during sunshine hours which can be used to cook rice during the evening and compared its performance with that of a standard solar cooker [77]. Nahar designed, fabricated, tested and compared the performance of a double reflector hot box solar cooker with a transparent insulation material (TIM) with a single reflector hot box solar cooker without TIM [78]. Sonune and Philip designed and developed a Fresnel type domestic SPRERI concentrating cooker which provides adequate temperatures needed for cooking, frying and preparation of chapattis [79]. Hussein et al. designed, constructed and tested a novel indirect solar cooker with outdoor elliptical cross section, wickless heat-pipes, flat-plate solar collector and integrated indoor PCM thermal storage and cooking unit under actual meteorological conditions of Giza, Egypt [80]. Hosny and Abou-Ziyan designed, constructed and carried out tests to compare the performance of two full tracking solar cookers, namely a paraboloid dish solar cooker (PDSC) and a booster mirror solar box cooker (BMSBC) during a winter season in Cairo under the same operating conditions [81]. El-Sebaii and Ibrahim constructed a box-type solar cooker with one (Model I) or four (Model II)

cooking pots and tested it under Tanta prevailing weather conditions [82]. Nahar designed, fabricated and tested a hot box solar cooker with used engine oil as a storage material so that cooking can be performed even in the late evening [83]. Esen fabricated and experimentally analyzed the performance of a solar cooking system using vacuum-tube collectors with heat-pipes containing a refrigerant as working fluid [70].

4. Solar driers

4.1. Study

Karsli made a comparative study of four types of air heating flat plate solar collectors: a finned collector with an angle of 75°, a finned collector with an angle of 70°, a collector with tubes and a base collector. He concluded that their efficiency depends significantly on the solar radiation and the surface geometry of the collectors and also that at higher reduced temperature parameter, the overall loss is lower [84]. Mahaprata and Imre conducted a parameter sensitivity analysis on a directly irradiated solar dryer with integrated collector. It is strongly suggested that an increase in solar radiation intensity has a larger effect upon the product temperature than upon the air temperature within the drying chamber [85]. Youcef-Ali and Desmons examined the influence of the aerothermic parameters and that of product quantity on the production capacity of an indirect solar dryer [86]. Salihoglu et al. investigated an economical solution to sludge management problem and recommended limited liming and solar drying as an alternative to only-liming the mechanically dewatered sludge [87]. Ayensu designed a solar dryer based on the principles of convective heat flow constructed from local materials and observed that it was twice as better compared to dehydration by open air sun-drying [88]. Bena and Fuller demonstrated an improved drying technology by combining a direct-type natural convection solar dryer and a simple biomass burner [89]. Otham et al. presented the design and performance of four advanced solar assisted forced convective solar dryers namely (a) the V-groove solar collector (b) the double-pass solar collector with integrated storage system (c) the solar assisted dehumidification system for medicinal herbs (d) the photovoltaic thermal collector system. They have proposed the possibility of production of a self-sufficient solar collector system that will not require any external electrical energy to run the system [90]. Gbaha et al. designed a direct type natural convection solar dryer and analyzed the influence of significant parameters governing heat and mass transfers, such as solar incident radiation, drying air mass flow and effectiveness in order to evaluate its thermal performances [91]. Forson et al. presented a mathematical model for drying agricultural products in a mixed-mode natural convection solar crop dryer (MNCSCD) using a single-pass double-duct solar air-heater which can predict the performance of the MNCSCD fairly accurately and therefore used as a design tool for prototype development [92]. Koyuncu presented various designs of flat plate solar energy air heating collectors for low temperature solar energy crop drying applications and concluded that many models of more or less efficient flat plate air dryers are used for drying agricultural products [93]. Ratti and Mujumdar developed a simulation code to predict the batch drying performance of a packed bed of particles subjected to time-varying air conditions and presented the effects of various key parameters of the process [94]. Purohit et al. developed a simple framework to facilitate a comparison of the financial feasibility of solar drying as against open sun drying and presented results of some exemplifying calculations [95]. Jannot and Coulibaly presented a new index, called the "evaporative capacity", for rating the performance of the solar air heater in a solar drier consisting of solar air heater and a drying chamber in series, a detailed method for calculating the evaporative capacity and a comparison of this new index with the thermal efficiency index, demonstrating its superiority [96]. Matrawy presented a mathematical model and solution procedure to study the effect of the metal vanes in a solar air collector and showed that a high efficiency can be achieved with the use of the metal vanes, particularly at smaller depths of the air duct [97]. Anil Kumar and Tiwari developed a thermal model to predict the jaggery temperature, the greenhouse air temperature and the moisture evaporated (jaggery mass during drying), during the drying of jaggery under natural convection conditions and showed that the analytical and experimental results for jaggery drying are in good agreement [98].

4.2. Development

Chen et al. developed a closed-type solar dryer associated with a photovoltaic system (PV) and found that the system produces high quality products in terms of sensory parameters [99]. Hossain and Bala used a mixed mode type forced convection solar tunnel drier to dry hot red and green chillies under the tropical weather conditions which led to a considerable reduction in drying time and dried products of better quality in terms of colour and pungency in comparison to products dried under the sun [100]. Shanmuga and Natarajan designed and fabricated an indirect forced convection and desiccant integrated solar dryer to investigate its performance under the hot and humid climatic conditions and discussed the system pickup efficiency, specific moisture extraction rate, dimensionless mass loss, mass shrinkage ratio and drying rate [101]. Madhlopa and Ngwalo designed, constructed and evaluated an indirect type natural convection solar dryer with integrated collector-storage solar and biomass-backup heaters and showed that the thermal mass stored part of the heat from both solar and biomass air heaters, thereby moderating temperature fluctuations in the drying chamber and reducing wastage of energy [102].

5. Solar ponds

5.1. Study

Karakilcik and Dincer studied both energetic and exergetic performances of a solar pond through efficiency analysis and developed exergy efficiencies for each zone of the solar pond through exergy balance equations [103]. Tamimi and Rawajfeh analyzed the thermal performance of evaporators and their model developed on lumped basis indicates that the efficiency of any solar evaporator is limited by the optical absorptivity of the saline water [104]. Velmurugan and Srithar reviewed various designs of solar pond, prospects to improve performance, factors affecting performance, mode of heat extraction, theoretical simulation, measurement of parameters, economic analysis and its applications [105]. Angeli et al. investigated the problem of development of salt concentration in a solar pond with thermodiffusion contribution using Computational Fluid Dynamics [106]. Punyasena et al. presented a focused study on time taken by the large area saltpan solar ponds to reach its stable conditions with heavy rainfall and the effect of wind mixing process on the stability of the pond at different climatic conditions. [107]. Agha et al. presented the results of a simple mathematical model for predicting the ratio of the evaporation pond (EP) area to that of a Salt Gradient Pond Area. The EP idea gives an attractive method of salt recycling by evaporation especially in areas of high rates of evaporation and low rates of rain [108]. Jubran et al. predicted the idea of convective layers on the sidewalls of a solar pond. A parametric study was conducted to predict the effects of wall tilt angle and salt concentration on the characteristics of the convective layers using

three-dimensional finite volume method for incompressible flows [109]. Spyridonos et al. presented a comparative study between two ponds one of whose free surface is covered by a thin layer of transparent paraffin oil and the other with transparent glass floating devices. The thermal storage efficiency of the two ponds were estimated using linear regression method and the first type of pond was preferred for use just after sunset [110]. Jaefarzadeh and Akbarzadeh discussed applications of simple methods like usage of floating rings, novel system of salt replenishment etc. to reduce the maintenance of a small solar pond [111].

5.2. Design

Sencan et al. used a number of methods for determining the performance parameters of an absorption heat transformer (AHT) used for increasing the measured low temperature values in the real small experimental solar pond [112]. Bezir et al. used the analytical functions derived for air and soil temperatures using the local meteorological data in simulations and determined the parameters affecting the solar ponds [113]. Garman and Muntasser used solar energy as an energy source in a salinity gradient solar pond for water desalination and made a mathematical model to study the factors affecting the size of solar pond to serve adequate thermal load sufficient to operate the desalination unit for the entire period of operation [114]. Agha et al. applied the evaporation pond idea to two types of water flushing (fresh water and sea water) under different scenarios and predicted the quantities of brine provided by the evaporation pond for both cases of surface water flushing [115]. Andrews and Akbarzadeh suggested an alternative method of heat extraction from salinity-gradient solar ponds with the aim of increasing the overall energy efficiency of collecting solar radiation, storing heat and delivering this heat to an application [116]. Husain et al. determined the optimum size of the non-convective zone for fast warm-up to increase the efficiency of the pond and analyzed the possibility of achieving fast warm-up and maximum heat collection capacity. They concluded that the ponds should be designed for warm up criterion than for steady state criterion [117].

5.3. Development

Kumar and Kishore constructed a 6000 m^2 solar pond at Bhuj in India with alternate clay and LPDE lining to supply heat and demonstrate technical and economic viability of solar pond technology in Indian context. The pond had a failure in lining and was re-designed and established successfully [118]. Rivera conducted an experiment using an experimental absorption heat transformer operated with water/Carrol mixture to demonstrate the feasibility of heat transformers to increase the temperature of the heat obtained from the solar ponds [119]. Hassairi et al. built a small laboratory solar pond of 2 m $\times$ 2 m $\times$ 1 m utilizing the natural brine salt from south of Tunisia and evaluated the efficiency of the pond by measuring the temperature and solar radiations evolved [120].

6. Solar architecture

6.1. Study

He et al. proposed the solar cooling strategies for tackling long, hot and humid summer which consisted of a multi-functional solar system and a method for indoor ventilation; the design included double walls and a triple roof in order to remove heat by ventilation of the building envelope [121]. Kischkoweit-Lopin studied a huge number of different daylighting systems that allow new and optimized ways of daylight utilization with the consideration that the different systems have to be used in the right way and that the used system is adjusted to the building and matches the requirements of the lighting for this special purpose [122]. Garde et al. studied all the methodology used for the application of ECODOM that led to a pedagogical reference document defining efficient passive solar cooling strategies and specifications for each component of the dwelling outer framework and likewise minimal porosity ratios to optimize natural ventilation [123]. Nielsen et al. compared the energy performance of different glazings or windows by producing diagrams which give the net energy gain based on the orientation, tilt, thermal transmittance (U-value) and total solar energy transmittance (g-value) [124]. Dai et al. presented a parametric analytical study on the enhancement of natural ventilation in a solar house induced by a solar chimney and a solid adsorption cooling cavity [125]. Nordell and Hellstrom studied a solar-heated low-temperature space-heating system with seasonal storage in the ground and the system performance has been evaluated using the simulation models TRNSYS and MINSUN together with the ground storage module DST. The study implies an economically feasible design for a total annual heat demand of about 2500 MWh [126]. Kummert et al. presented the application of optimal control to auxiliary heating of a passive solar commercial building based on the principle of anticipating the building behavior using a model and forecasting of disturbances in order to compute the control sequence that minimizes a given cost function over the optimization horizon resulting in significant energy savings while improving the comfort level in the buildings [127].

6.2. Design

Wen and Smith developed an analysis that allows an examination of the spatial distribution of absorbed solar energy for a room that uses a geometrical-based method to describe the location and magnitude of the directly incident solar beam energy for each discrete surface and the measured solar energy values were used to compute the absorbed solar energy as a function of time [128]. Sanchez proposed a new system for heat dissipation in air-conditioning facilities incorporating cool solar roof (CSR) which is the integration of four classical elements-earth, wind, water and fire for technological innovation and environmental care [129]. Maneewan et al. proposed a numerical investigation on attic heat gain reduction by using thermoelectric modules integrated in a conventional thermoelectric roof solar collector (TE-RSC) that generates a direct current used to drive a ventilating fan for cooling TE-RSC and thus enhancing attic ventilation thereby reducing ceiling heat gain [130]. Fang and Li developed a three-dimensional transient heat transfer model of a lattice passive solar heating wall (LPSHW) based on which a computer simulation program was developed using FORTRAN to simulate and evaluate the transient thermal performance, to analyze the sensitivity and effect of climate and thus optimizing the LPSHW structural parameters [131]. Belusko et al. developed a mathematical model of the glazed collector and a system that significantly increases the performance at the expenditure of lesser conventional energy thereby improving cost effectiveness [132]. Badescu developed a ground heat exchanger model based on a numerical transient bi-dimensional approach that allows computation of ground temperature at the surface and at various depths and concluded that the energy delivered by the ground heat exchanger depends significantly on different design parameters like depth, diameter and material of the pipe [133].

7. Solar air-conditioning

7.1. Study

Grossman describes the current trends in solar powered air-conditioning systems in which he had substantiated that double and

triple effect chillers had better COP than the single effect chillers while using LiBr/water as the working fluid and also highlighted the performance of open cycle absorption system and the need to replace it with closed cycle sorption systems [134]. Elsafty and Al-Daini made an economical comparison of solar powered single, double effect vapor absorption air-conditioning system and a vapor compression system using present worth comparison method and equivalent annual comparison method and suggested that double effect solar air-conditioning system is more suitable for applications [135]. Gommed and Grossman investigated the use of liquid desiccant system, which absorbs humidity from the process air by direct contact with desiccant and desiccant regeneration by direct contact with external air stream in a 16 kW solar cooling and dehumidification system using LiCl/water as the working fluid and reported a COP of 0.8 [136]. Khedari et al. conducted a feasibility study of using dry agricultural wastes like coconut coir and durian peel as a desiccant for an open cycle air-conditioning system and the comparison shows that coconut coir can absorb more moisture than durian peel but lesser than silica gel under given operating conditions [137]. Hamed presented a study on the desorption characteristics of a packed porous bed in which burned clay is used as a desiccant carrier impregnated with calcium chloride, found out that the mass transfer rate has a significant effect on the concentration gradient in the bed and at specified operating conditions the desorption rate is higher compared with adsorption [138]. Breesch et al. investigated the methods of passive cooling in a low energy office building by using natural night ventilation and earth-to-air heat exchangers and upon simulations with TRNSYS-COMIS revealed that natural night ventilation is a better option than earth to air heat exchangers for summer thermal comfort [139].

7.2. Design

Papadopoulos et al. focused on the state of art solar thermal technologies combined with sorption refrigeration techniques to cover the cooling demand of residential and commercial buildings [140]. Arbel and Sokolov used R-142b as a refrigerant instead of R-114 in a solar powered ejector air conditioner in order to update their previous work which proved to be an environmentally compatible and efficient system [141]. Kabeel proposed a new system of air conditioning with honey comb desiccant rotary wheel made of iron wire and clothes layer impregnated with calcium chloride solution and studied the effect of solar intensity and airflow rate on system regeneration and obtained empirical relations for wheel effectiveness and removal of moisture [142]. Khattab and Barakat presented a detailed mathematical model about the performance of a low temperature, low pressure solar steam-jet cooling cycles for comfort air conditioning which includes the performance of the steam jet ejectors thereby developing a simulation program which analyzes the overall system performance under different design and operating conditions [143]. Jiangzhou et al. suggested a new method of locomotive air-conditioning system using zeolite/water driven by waste heat from exhaust gas of the engine which replaces the vapor compression system which has leakage and power conversion problems [144]. Vokas et al. suggested a new approach of domestic heating and cooling by using solar PV/T collectors with an efficiency of 9% by studying the performance of the collector in varying geographical regions and different total surface areas and confirmed that PV/T technology offers a feasible solution for the problem of domestic heating and cooling [145].

7.3. Development

Ali et al. designed and modeled a new prototype of solar energy driven air-conditioning system in Tunisia using meteorological data for summer and winter modes of operation and can be used for predicting the behavior in various climatic conditions [146]. Belarbi et al. developed a model for water spray evaporation which estimates the time needed to evaporate the drops and this can be used for passive cooling of buildings [147].

8. Solar chimneys

8.1. Study

Zhou et al. carried out simulation studies to investigate the performance of a pilot scale solar chimney power plant for different solar intensities by varying collector area and chimney height and the simulated results closely agree with the measured values [148]. von Backstrom et al. investigated the turbine characteristics by developing analytical equations in terms of turbine flow, load coefficient and degree of reaction and their influence on turbine efficiency and proved that if applied to a large solar chimney plant, a peak turbine total-to-total efficiency of around 90% is attainable but not necessarily over the full range of plant operating points [149]. Pretorius et al. studied the influence of parameters like turbine inlet loss coefficient, quality collector roof glass and various types of soil on the performance of a large scale solar chimney power plant based on a recently developed convective heat transfer equation [150]. Mathur et al. investigated the effect of the ratio between height of absorber and gap between the glass and the absorber in a solar chimney used for room ventilation and found out that highest rate of ventilation induced with the help of solar energy was 5.6 air changes per hour in a room of 27 m^3, at solar radiation 700 W/m^2 on vertical surface with the stack height-air gap ratio of 2.83 for a 1 m high chimney [151]. Chantawong et al. reported the thermal performance of glazed solar chimney walls under tropical climatic conditions of Thailand in a southern faced wall of a room of prescribed dimensions and concluded that the temperature difference between room and ambient was less than that with a single layer clear glass window [152].

8.2. Design

Ong and Chow proposed a mathematical model to predict the performance of a solar chimney under varying ambient and geometrical features for an air gap between 0.1 and 0.3 [153]. Bernardes et al. developed a numerical model to describe the performance of solar chimneys by taking into account the effect of various parameters like ambient conditions and structural dimensions on the power output [154].

9. Solar power plants

9.1. Study

von Backstörm and Fluri conducted a study and developed two analyses for finding the optimal ratio of turbine pressure drop to available pressure drop in a solar chimney power plant for maximum fluid power [155]. Segal and Epstein optimized the important components of a solar central receiver power plant like receiver, heliostat field and power block thus maximizing their efficiency and suggested that beyond a certain limit of the operating temperature the overall system efficiency decreases [156]. Quaschning examined 61 sites in Europe and North Africa which receive around 923–2438 kWh/m^2 and conducted a techno economic system comparison of photovoltaic and concentrating solar thermal power systems [157]. Martínez and Almanza studied the temperature profile around the absorber tube of a parabolic trough concentrator with low fluid flow of water under saturated

and low pressure conditions and by keeping feed flow as the control variable and solar irradiance as the restriction variable the theoretical analysis agreed well with the experimental values [158].

9.2. Design

Kribus suggested a solar triple cycle in which a high temperature MHD generator and two additional cycles connected in series is powered by solar heat at a temperature of 2000 °C and the efficiency reported is higher than the combined cycle scheme [159]. Imenes et al. proposed a new strategy by which the collected beam is split into optimized components for two or more spectral receivers and this is achieved based on flux mappings produced by ray tracing methods for a multi-tower solar array central receiver system in Australia [160]. Tina et al. presented a probabilistic approach based on convolution technique to assess the long-term performance of a hybrid solar-wind power system (HSWPS) for both stand-alone and grid-linked applications and also included a numerical example to illustrate the validity [161]. Zarza et al. presented a conceptual design of the first solar power plant using direct steam generation (DSG) in a parabolic-trough solar field producing 410 °C and 70 bar superheated steam delivering a power output of 5 MW [162]. Koutrolis et al. proposed a new methodology to optimize the size of stand alone photovoltaic/wind generator systems using genetic algorithms and this hybrid system proved to have a lower system cost than PV or WG system alone [163]. Hong et al. proposed a new solar thermal power cycle in which the solar energy is used to decompose methanol into syngas and combusting it with air resulting in an efficiency of 35% at a collector temperature of 220 °C [164].

9.3. Development

Yang et al. developed a hybrid solar wind system optimization sizing (HSWSOS) model for optimizing the capacity sizes of different components of hybrid solar wind power generating systems with battery bank [165]. Stuetzle et al. developed a non-linear model to control the flow rate of the heat transfer fluid based on the outlet temperature for a 30 MW SEGS power plant for both summer and winter conditions when the plant is operating in pure Solar mode [166]. Dufo-Lopez and Bernal-Agustín developed a HOGA (hybrid optimization by genetic algorithm) Program using C++ and compared the model with a stand alone PV system. The results show the economical advantages of the PV hybrid system, PV only system and diesel only systems [167]. Lovegrove et al. conducted experiments on solar driven ammonia based closed loop thermo chemical energy storage system in which solar energy is collected from a dish type solar concentrator using a cavity receiver containing reactor tubes filled with iron based catalyst material and theoretical investigations show that electrical power potential from ammonia synthesis reactors can be maximized through appropriate choice of operating temperature and the system showed an efficiency of 53% [168]. Zhang et al. established an irreversible model of solar driven Brayton heat engine considering various heat losses, external and internal irreversibilities thereby optimizing the solar collector temperature and the temperature ratio of the isobaric process [169]. Bilgen et al. designed a solar chimney system of 5 MW capacity for high latitudes, evaluated its performance, developed a mathematical model and code using MATLAB and reported the overall system efficiency to be less than 0.5% [170]. Schwarzbözl et al. presented the design and performance assessment of several prototype plants with different power levels of 1 MW, 5 MW and 15 MW respectively using advanced software tools and revealed various features like cost assumptions, economic analysis and cost reduction potentials [171]. Heller et al. designed and installed a solar powered gas turbine system capable of delivering pressurized air at 1000 °C and reported that the cost and performance of the system appears to be a promising option in the near future [172].

10. Solar stills—water purification and distillation

10.1. Study

Porta et al. found that the overall thermal inertia effects can be adequately represented by a single non-dimensional quantity referred as thermal inertia slenderness ratio. Simulation of the calibrated mathematical model illustrates the influence of thermal inertia on performance [173]. Tiwari et al. reviewed the works on solar distillation, its present status and future perspective and also classified the distillation units [174]. Tzen and Morris presented technologies about renewable energy sources (RES) desalination and described its coupling with PV-reverse osmosis, wind-mechanical-vapor compression, geothermal-multi-effect distillation [175]. Voropoulos et al. investigated the behavior of a conventional greenhouse-type solar still coupled with hot water storage tank heated by a solar collector field, based on which a simple and efficient mathematical model that can be used as a valuable tool for testing an existing solar distillation system was evaluated [176]. Tripathi and Tiwari presented the thermal analysis of passive and active solar distillation system by using solar fraction inside the solar still with AUTOCAD 2000 for given solar azimuth and altitude angle and latitude, longitude of the place and the experimental observation gave fair results [177].

10.2. Design

Chouikh et al. performed the numerical analysis for the natural convection flow resulting from the combined buoyancy effects of thermal and mass diffusion in an inclined cavity with a mathematical model for solar brackish water desalination unit and found that the desirable flow for enhancing the performance of the solar distiller is characterized by a single rotating cell that allows enough time for vapor cooling [178]. Vorayos et al. created mathematical models of each main component in the solar ethanol distillation system and the system simulation determined the yield and its concentration at any given condition [179]. García-Rodríguez suggested an idea of coupling renewable energy resources like solar photovoltaic energy, wind energy, geothermal energy in desalination systems and also said that pretreatments permit increase in performance [180]. Chaibi and Jilar presented the concept in which the roof transmission is reduced as solar irradiation is absorbed by flowing water on a glass sheet covered by a top glass sheet so that the fresh water is evaporated, condensed and collected at the roof eaves as desalinated water [181].

10.3. Development

Ward designed and tested a black plastic sheet covered solar water purifier which is rugged, lightweight, portable and suitable for remote outback that will readily convert impure water such as bore, sea, brackish, urine, radioactive, arsenic contaminated, effluent etc into pure drinking water with a TDS content of 1–2 ppm [182]. Kumar and Tiwari developed a thermal model to determine the convective mass transfer for different Grashof Number range in solar distillation process based on simple regression analysis and calculated the percentage deviation between experimental and theoretical results within an accuracy of 12% [183]. Duff and Hodgson built a passive solar water

pasteurization system based on density difference flow principles which eliminates boiling problems encountered in previous designs and is found suitable for solar water pasteurization processes [184]. Hongfei et al. designed a new solar desalination unit with three effects regeneration based on the analysis of the mechanism of falling film evaporation and condensation and the results indicated that it has relatively high performance ratio and also excelled in transient-state performance [185].

11. Conclusion

A detailed literature survey of major solar thermal technologies comprising of solar water heaters, solar cookers, solar driers, solar ponds, solar architecture, solar conditioning, solar chimneys, solar power plants and solar stills was performed. The review gives a brief overview of the developments in each of these key areas of technology in view to either raise the performance of the presently used system or to build a new system which employs a great deal of innovation and gives better results than the present ones, both at the same time. Thus the paper explicitly points out the areas in solar thermal technologies where there is scope for future research.

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